Vector Boson + jets production at the Tevatron

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on behalf of the CDF and D0 collaborations

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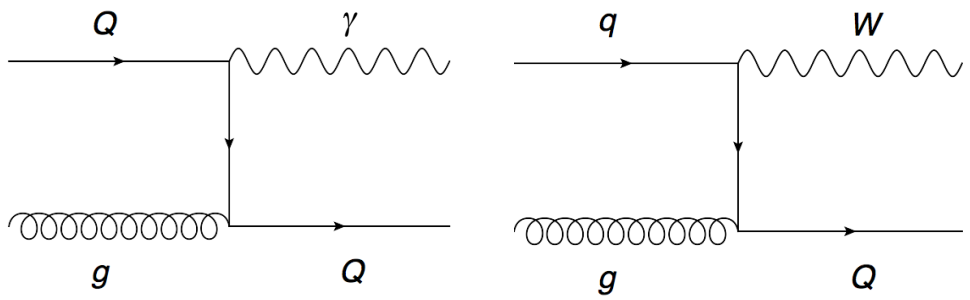
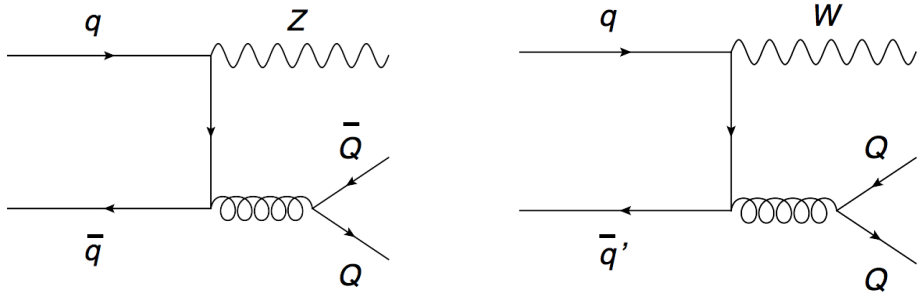
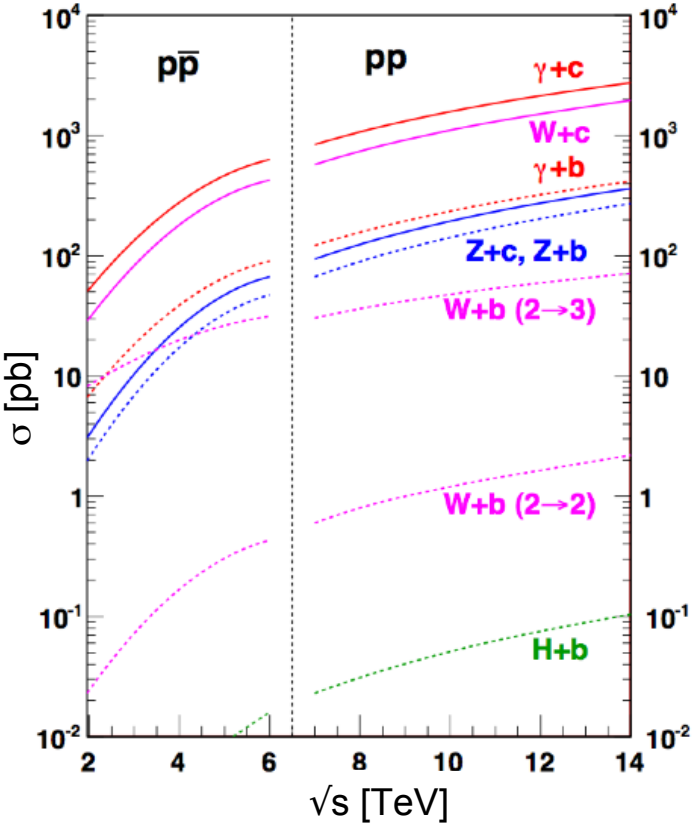
Vector boson plus heavy flavor jets production is a good probe of QCD…

- First-order production is sensitive to the proton PDF



- Provides stringent test of perturbative QCD calculations

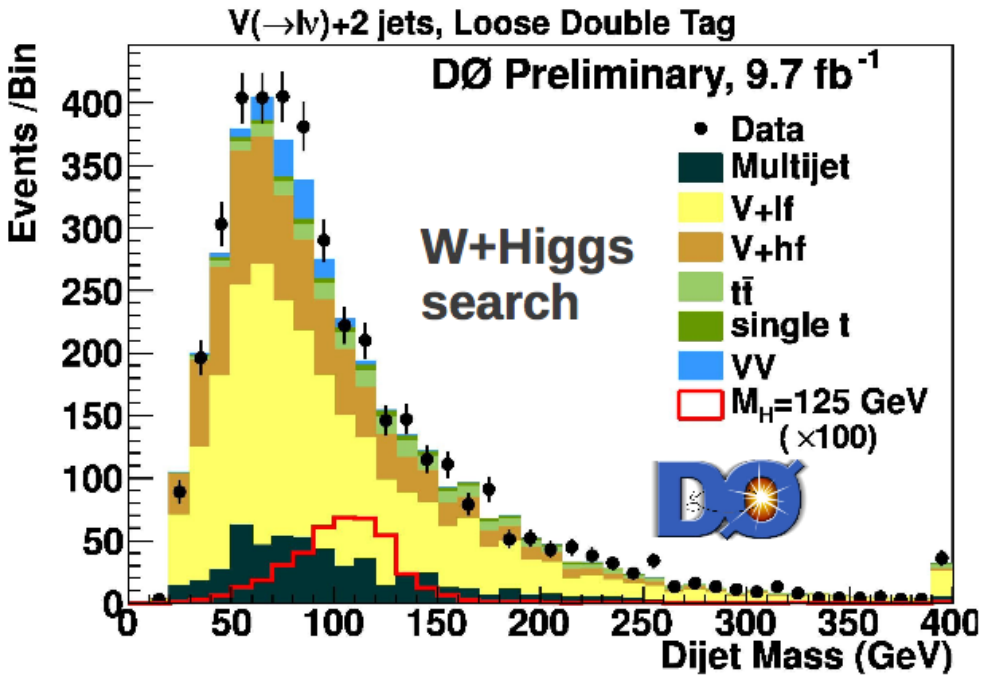




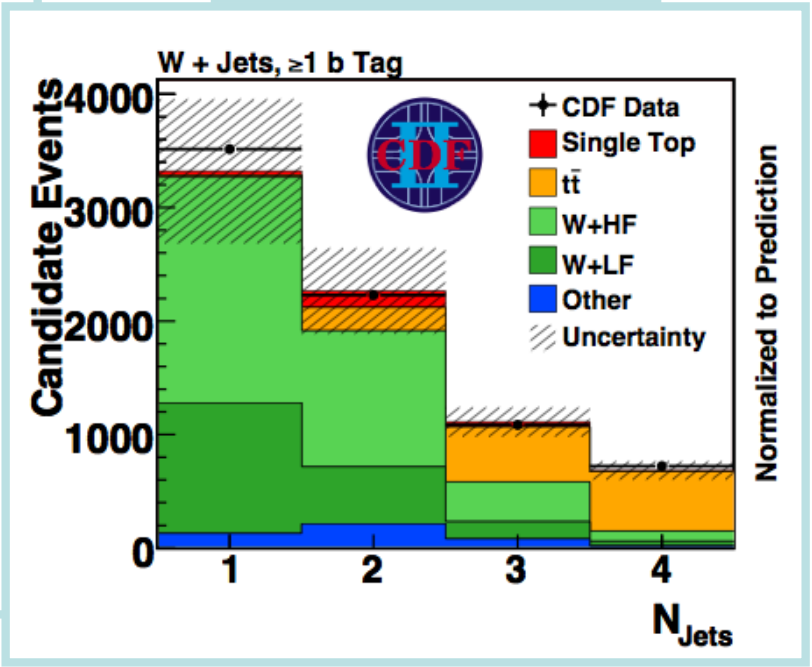
- Small h.f. σ = challenging!

…and it is also an important model for background in other searches

e.g. for Higgs…



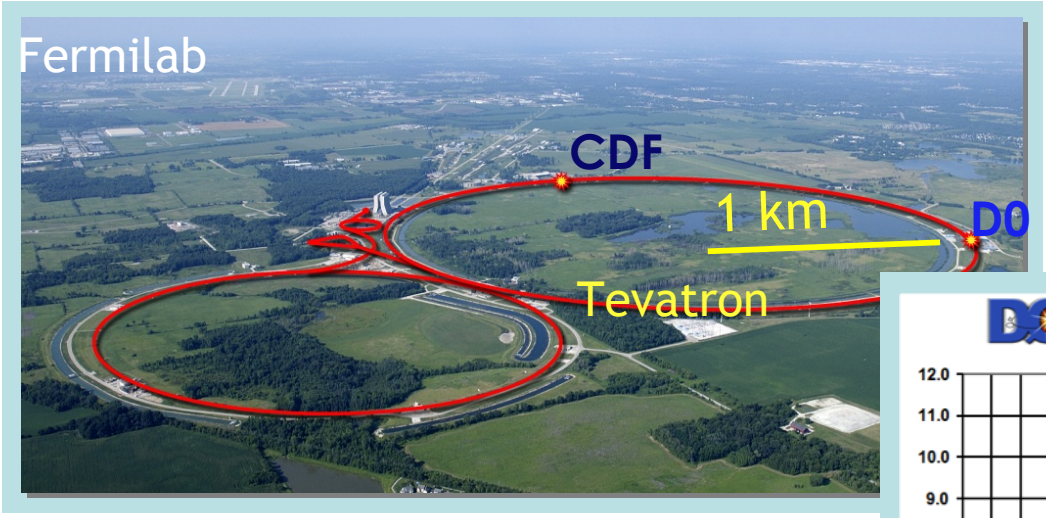
… and single top



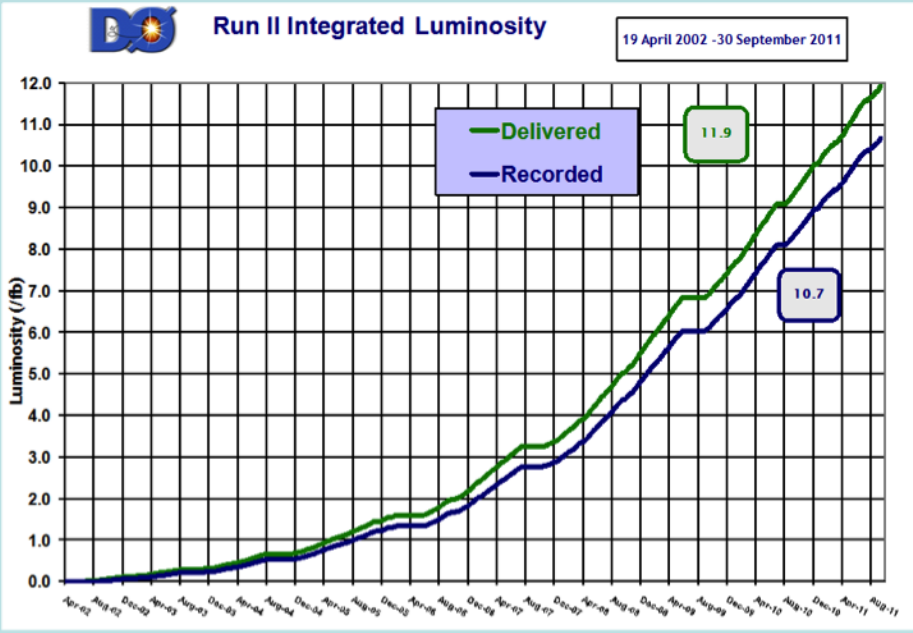
As well as new physics searches (e.g. dark matter candidates)

The Tevatron provided a decade's worth of $\sqrt{s}$ =1.96 TeV $p\bar{p}$ data

- Collided $p\bar{p}$ bunches at $\sqrt{s}$=1.96 TeV through 30/09/2011



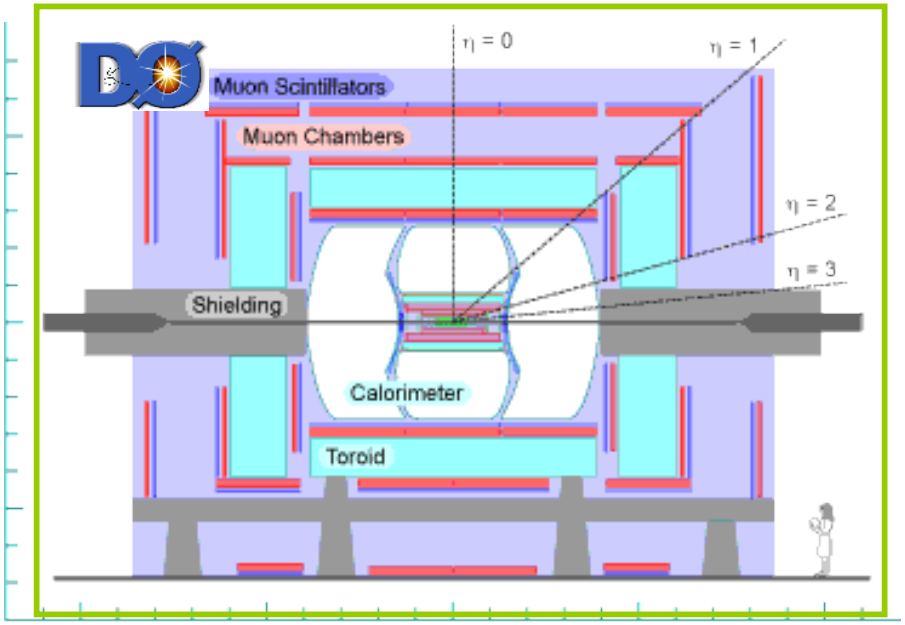
- Peak luminosity ~3-4 x 10^{32} cm^{-2} s^{-1}

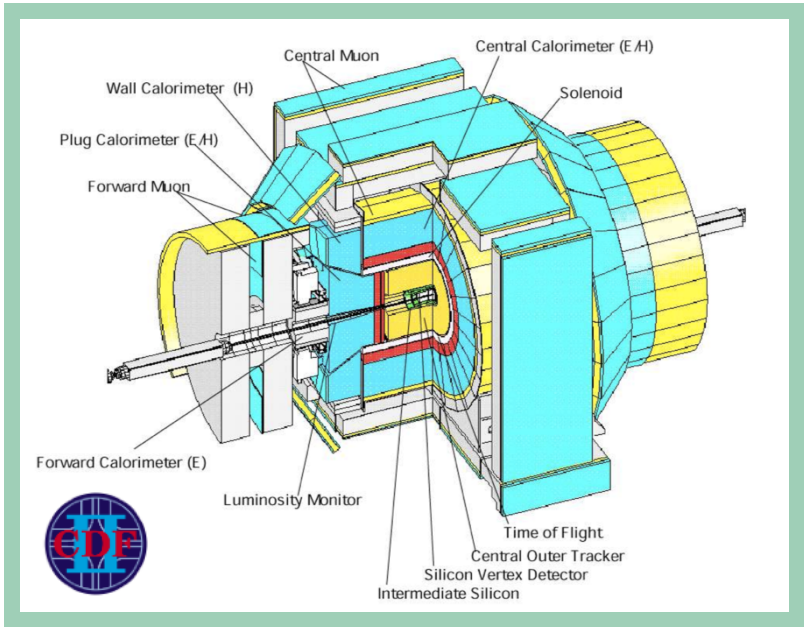


- The CDF and D0 experiments recorded up to ~10 fb^{-1} each

While designed for high-p_T physics, CDF & D0 are powerful h.f. tools

- High CM energy means more species of h.f production---even compared to B factories
- Precision vertex reconstruction capabilities (CDF & D0)
- Excellent tracking for mass resolution (CDF)





- Powerful trigger on displaced vertices (CDF)
- Charge symmetric detector (D0)
- Hermetic calorimeter and excellent energy resolution (D0)

A legacy of great V + jets/heavy flavor results! And now some more…

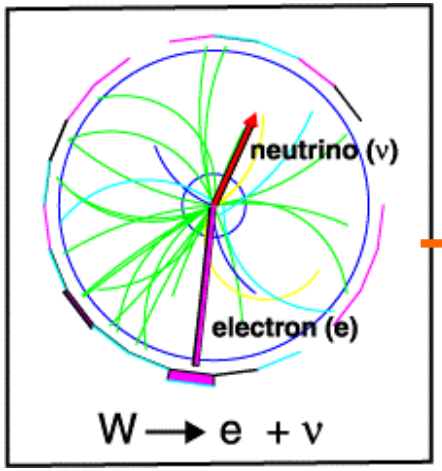
Most recently:


Final State	Luminosity	Detector	Publication
Z+b	9.7 fb^{-1}	D0	[PRD **87**, 092010 (2013)]
Z+c	9.7 fb^{-1}	D0	[PRL **112**, 042001 (2014)]
γ+b_{jets}	8.7 fb^{-1}	D0	[Phys. Lett. B. (Submitted) arXiv:1405.3964]
W/Z+Y	9.1 fb^{-1}	CDF	[CDF Public Note 11099 (Preliminary)]
W/Z+D*	9.7 fb^{-1}	CDF	[CDF Public Note 11087 (Preliminary)]

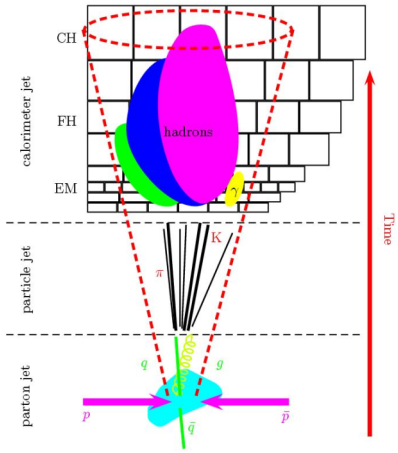
This is what we'll focus on in this talk!

A standard V+jets analysis begins with a high-p_T lepton/photon trigger

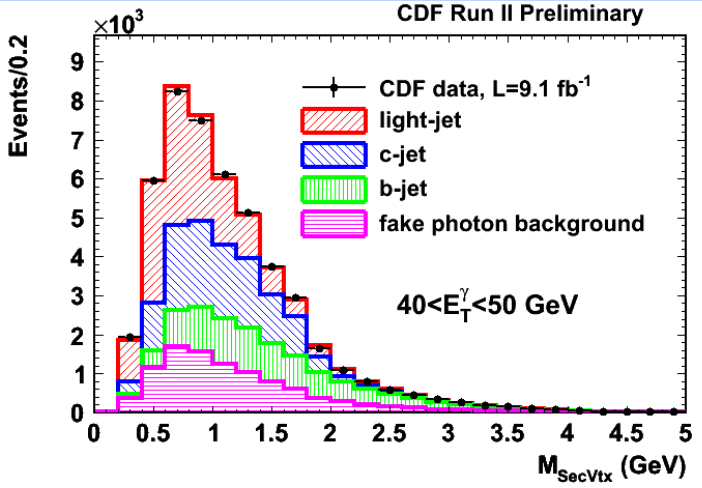
- Lepton is paired with MET (for W) or an oppositely-signed lepton (for Z)
- Or photon is compared to shower profiles



- Midpoint jet algorithm defines jets within a cone of R=0.4-0.7

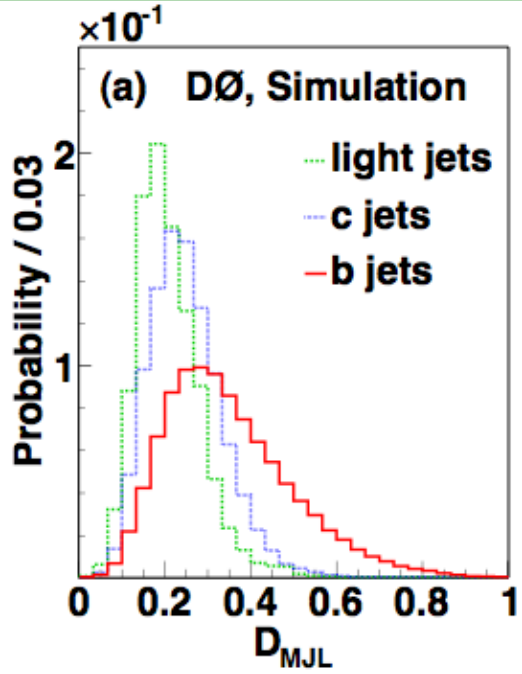


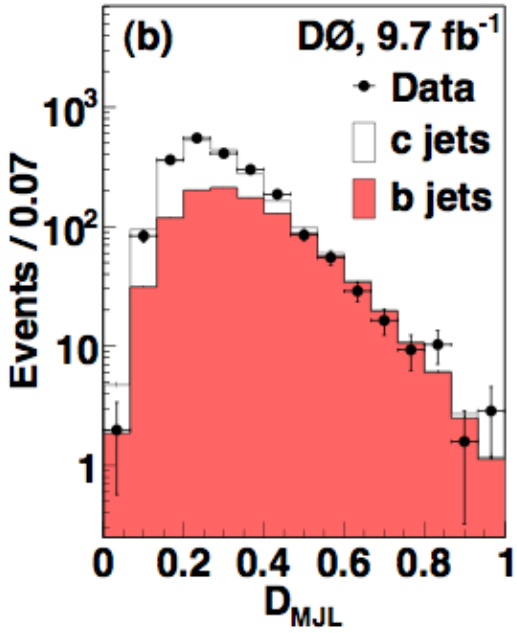
- For heavy-flavor, a secondary vertex is tagged. M_{inv} of this vertex can be fit to *bottom* / *charm* / *light flavor* profiles.
- Detector-level cross-sections are unfolded back to particle level with MC and data-driven techniques.



Recently, D0 made the first observation of $Z+c_{jet}$ at the Tevatron

- Jet flavor is identified using a combination of jet properties:





Used discriminant:

D_{MJL} = 0.5 x (M_{SV}/5 GeV - ln(JLIP)/20)

M_{SV} = mass of the jet sec. vtx.
JLIP= jet lifetime impact parameter

- Jets required to have p_T >20 GeV, $|\eta|$<2.5

Jets in *Z* events had more charm than predicted by NLO, on average

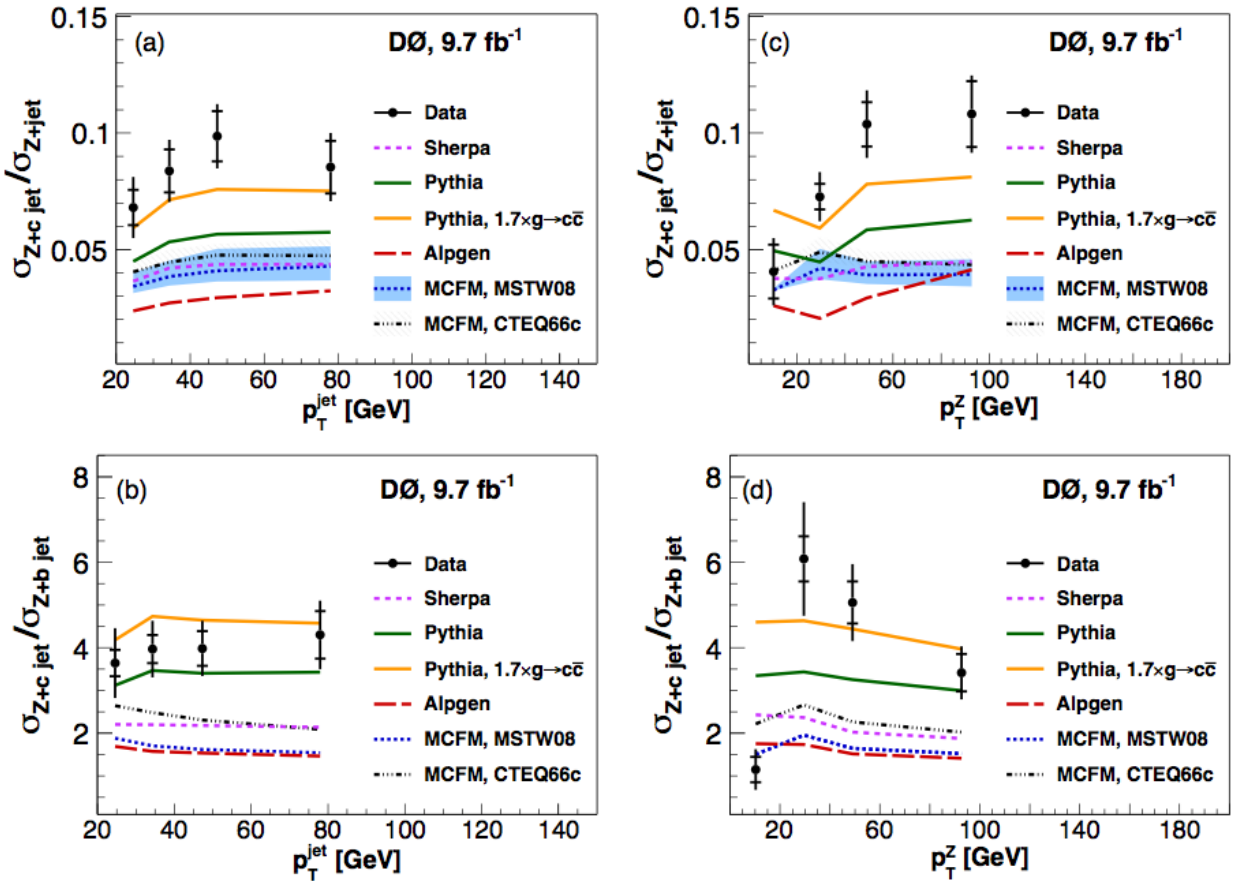
- Measures

$$\frac{\sigma(Z + c_{jet})}{\sigma(Z + \text{jet})} \text{ and } \frac{\sigma(Z + c_{jet})}{\sigma(Z + b_{jet})}$$

- Integrated *c*-jet fractions 2.5 times higher, on avg, than NLO predictions

Measured	(stat)	(syst)
$R_{c/jet}$ = 8.92	± 0.0053	± 0.0089
$R_{c/b}$ = 4.00	± 0.21	± 0.58

- Results agree best with Pythia + enhanced $g \to c\bar{c}$ splitting ratio



(Blue bands represent variation of scale by factors of 2, 1/2)

This supplements earlier D0 results in $Z+b_{jet}$ events

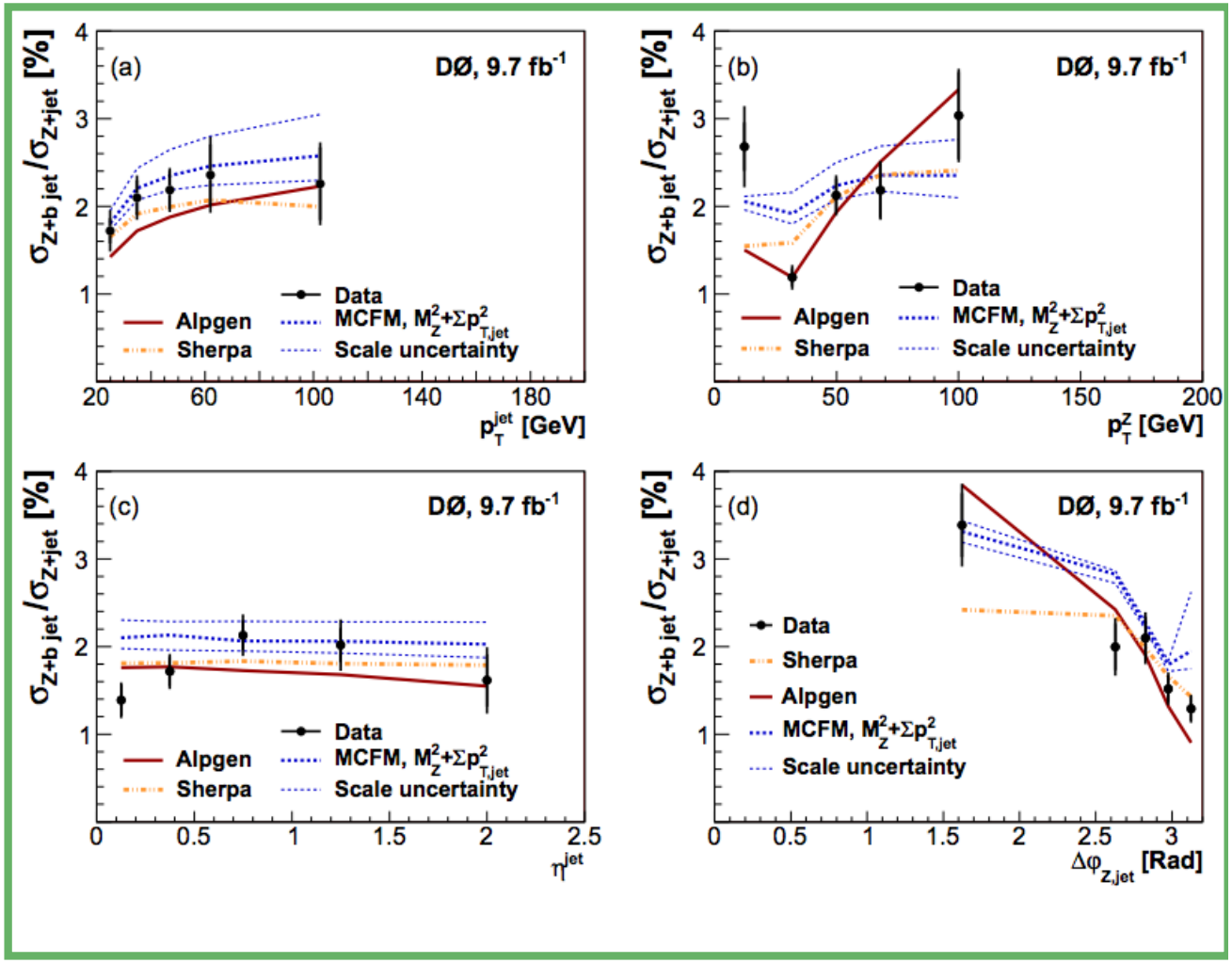
- Measured $\sigma(Z+b_{jet})/\sigma(Z+jet)$ as a function of several kinematic variables:
- Differential results by $p_T(Z)$, $\Delta\phi(Z,jet)$ agree best with ALPGEN, SHERPA, respectively
- Integrated fraction $\sigma(Z+b_{jet})/\sigma(Z+jet)$ for $p_T(jet)>20$ GeV, $|\eta^{jet}|<2.5$ as measured in data:

$$0.0196 \pm 0.0012\,(\text{stat}) \pm 0.0013\,(\text{syst})$$

agrees with NLO pQCD†:

$$0.0206^{+0.0022}_{-0.0013}$$

†[PRD **69**, 074021 (2004)]

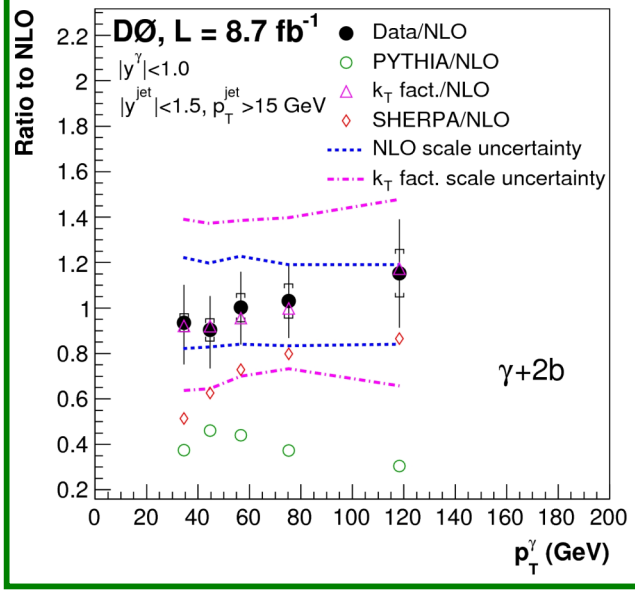


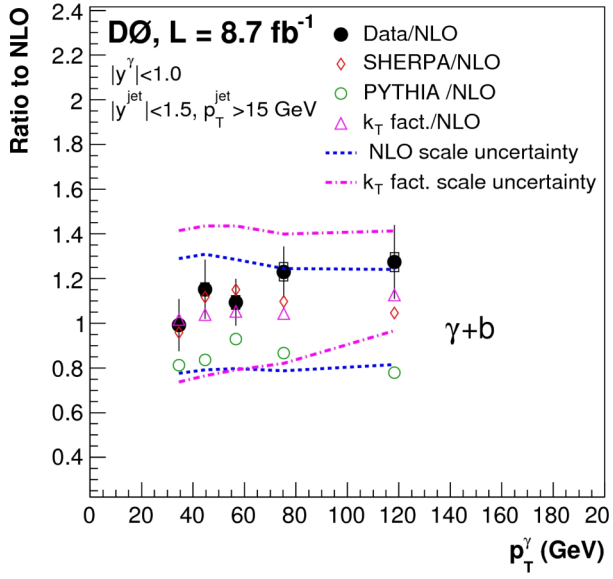
A D0 study of photons plus *b*-jets extends this work in a new direction

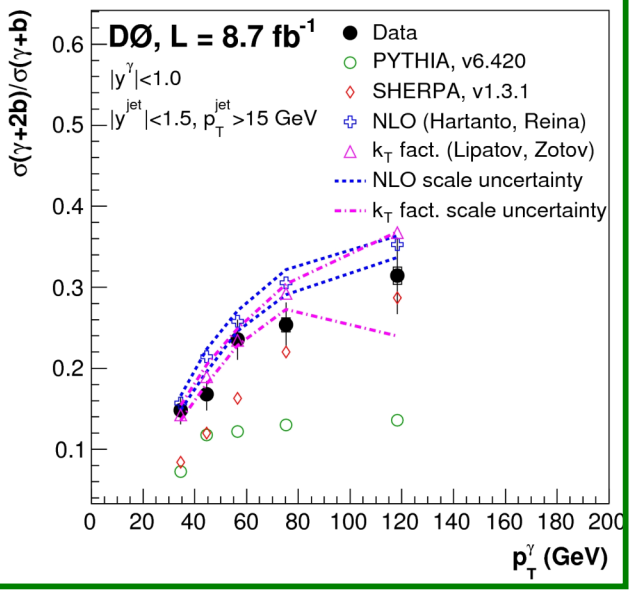
- Tests pQCD at high Q^2 over wide range of parton momentum fractions

$gb \rightarrow \gamma b$	Dominates at low to moderate $p_T(\gamma)$
$gg / q\bar{q} \rightarrow \gamma b\bar{b}$	Dominates at high $p_T(\gamma)$

- Photons selected with $|y|<1.0$, $30 < p_T < 200$ GeV.
- NLO predictions good; SHERPA predicts shape, but not scale.

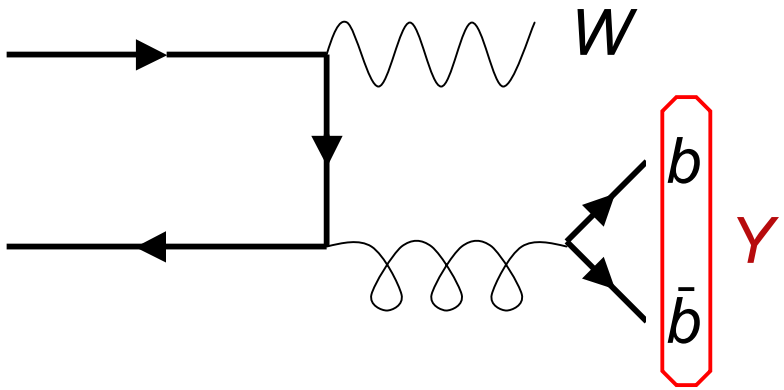


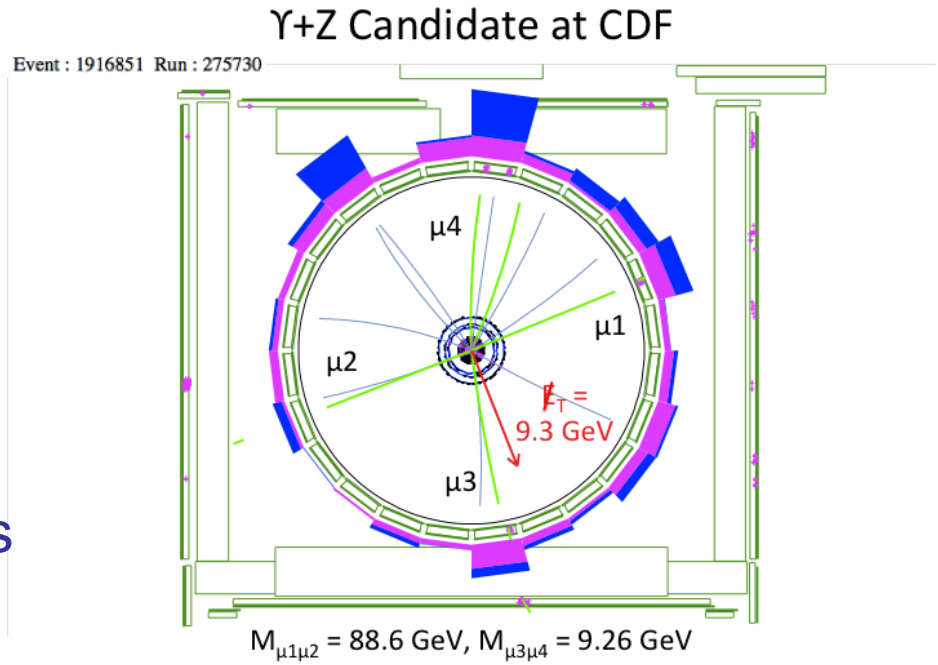




New CDF *Υ+W/Z* measurements provide upper limits on SM & SUSY searches

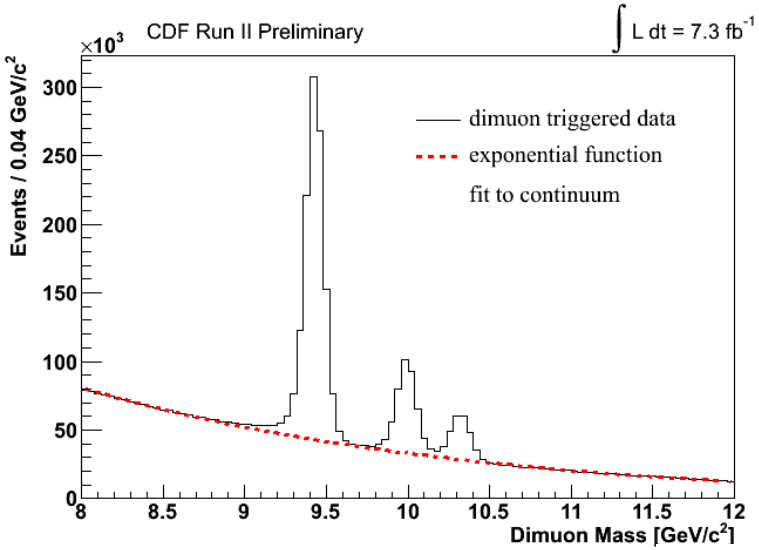
- *Υ+W/Z* is a rare process with a SM cross-section predicted to be outside the range of sensitivity of the Tevatron





- Sensitive to non-relativistic QCD models and new physics (e.g. a SUSY *Higgs→Υ+W/Z*)

CDF has observed no *Y+W/Z* excess, setting the best σ limits on $p\bar{p} \rightarrow Y+W/Z$



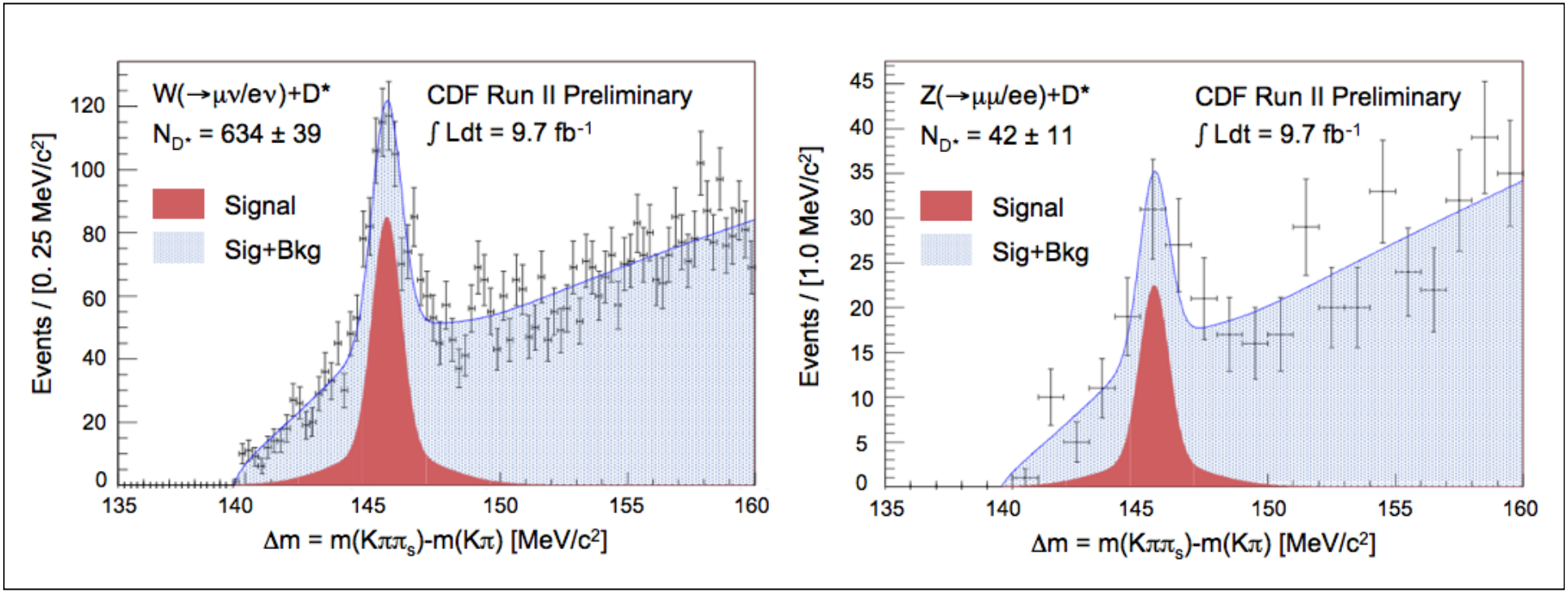
- Looks for $Y(1s) \rightarrow \mu\mu$ and *W/Z* charged lepton decays with standard cuts
- Observes 1(1) *Y+W(Z)* candidate over an expected bkg of 1.2±0.5 (0.1±0.1) events
- Sets 95% C.L. cross-section limits:

	$\Upsilon + W$	$\Upsilon + Z$
expected limit (pb)	5.6	13
observed limit (pb)	5.6	21
Run I observed limit (pb)	93	101

Table 5: Cross section limits at 95% CL for ΥW and ΥZ production. This analysis utilizes 9.4 fb^{-1} of CDF II Run II data. The Run I analysis utilized 83 pb^{-1} of CDF Run I data.

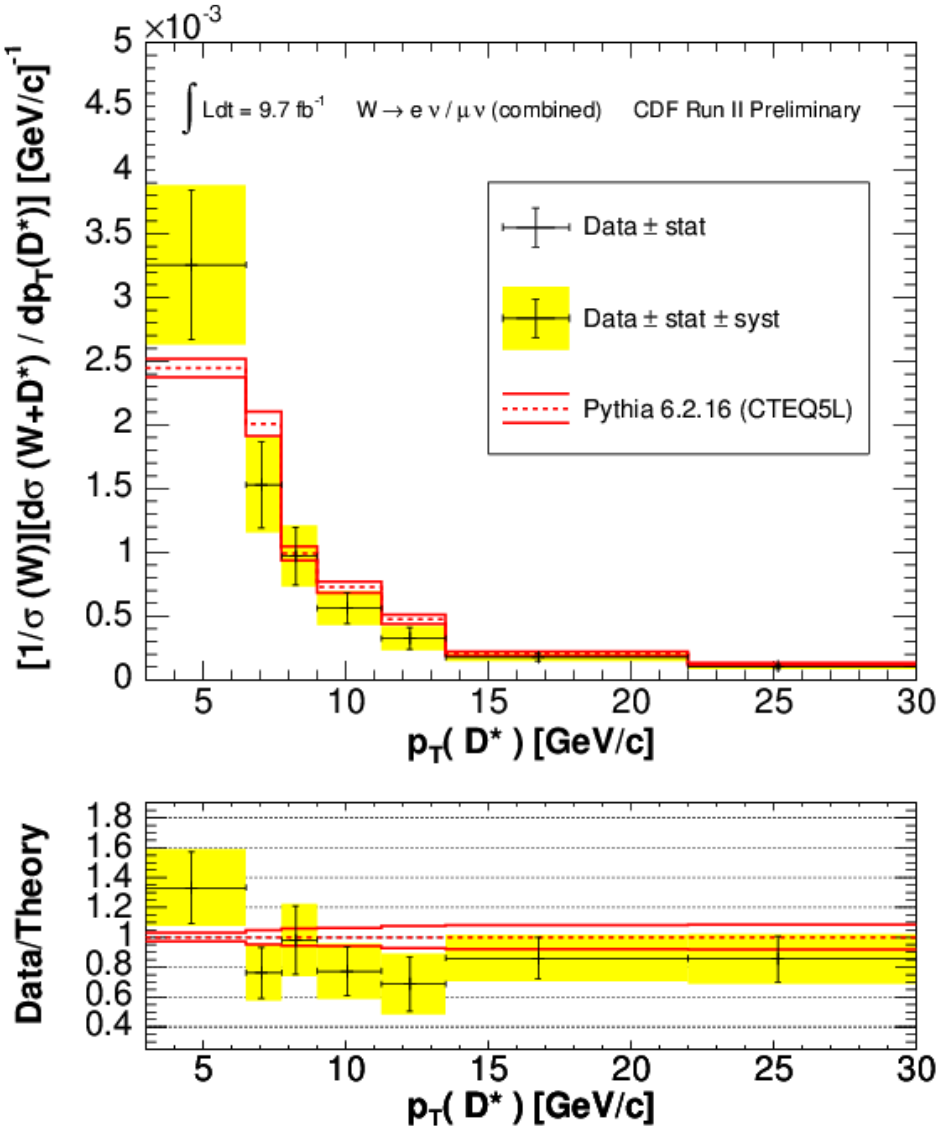
CDF has also measured $W/Z+D^*$ production for $p_T(D^*) > 3$ GeV

- Fully-reconstructs $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ at the track level in W/Z events



- Signal discriminant is mass difference between D^* and D^0 vertices. Background is reduced with a neural network to improve stat. unc.

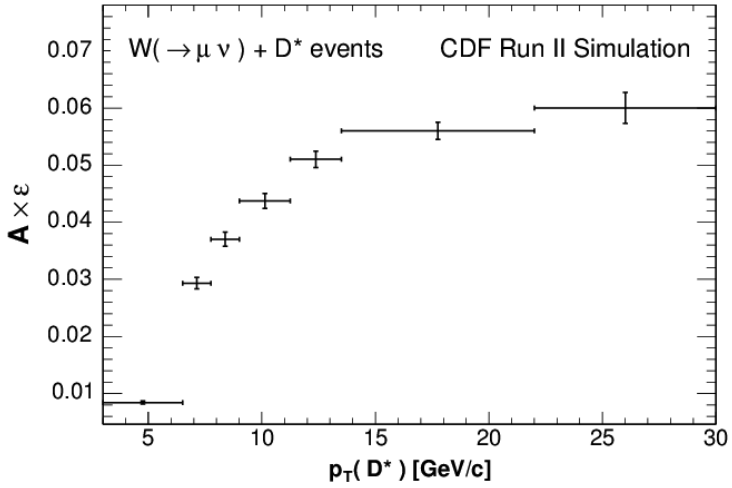
Measurements of $\sigma(W/Z+D^*)/\sigma(W/Z)$ compare favorably with simulation



…both differentially, and for inclusive sample:

Production process ($p_T(D^*) > 3$ GeV/c)	CDF Run II Preliminary $\int \mathcal{L}dt = 9.7$ fb^{-1} $\sigma(V+D^*)/\sigma(V)$ (%) $\pm$(stat) $\pm$ (syst)	Pythia 6.2.16 (CTEQ5L) $\sigma(V+D^*)/\sigma(V)$ (%) $\pm$ (pdf unc)
$W(\to e\nu) + D^*$	$1.74 \pm 0.21 \pm 0.17$	1.77 ± 0.07
$W(\to \mu\nu) + D^*$	$1.75 \pm 0.17 \pm 0.05$	1.77 ± 0.07
Combined results: $W(\to e\nu/\mu\nu) + D^*$	$1.75 \pm 0.13 \pm 0.09$	1.77 ± 0.07
$Z(\to ee) + D^*$	$1.0 \pm 0.6 \pm 0.2$	1.36 ± 0.05
$Z(\to \mu\mu) + D^*$	$1.8 \pm 0.5 \pm 0.2$	1.36 ± 0.05
Combined results: $Z(\to ee/\mu\mu) + D^*$	$1.5 \pm 0.4 \pm 0.2$	1.36 ± 0.05

- Can identify D^* down to $p_T(D^*) > 3$ GeV



Summary

- The full CDF/D0 datasets continue to provide interesting new vector boson plus jets results, adding to their legacy

- In the past year, have provided three firsts in $p\bar{p}$ collisions:
  - first observation of $Z+c$
  - first observation of $W/Z+D^*$ at low p_T ($p_T > 3\ GeV$)
  - first measurement of isolated γ plus b pair production

- Have also placed the current best limits on $p\bar{p} \rightarrow Y+W/Z$ production, and measured b_{jet} fractions in Z+jet events

- These analyses will benefit MC tunings, and many future analyses at both the Tevatron and LHC---more to come as we continue to explore the full datasets!

Further Reading

- All results discussed in this talk are available on the CDF and D0 Public Results pages:

CDF:

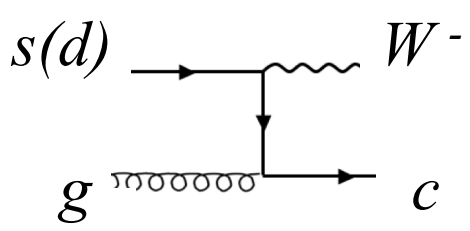
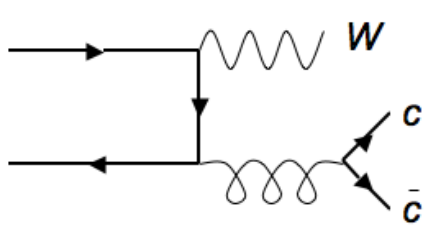
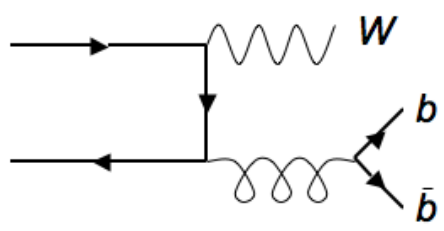
http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

D0:

http://www-d0.fnal.gov/results/

CDF $W/Z+D^*$ analysis also splits the $W+D^*$ signal by production process

- There are three major contributions to our final $W+D^*$ signal:

$s(d)+g \rightarrow W+c$	$W+g(\rightarrow c\bar{c})$	$W+g(\rightarrow b\bar{b})$, $B \rightarrow D^*+X$
		
14 ± 6%	73 ± 8%	13 ± 5%

- The percentages above are derived using neural networks, and by exploiting sign correlations in the W and c of Process 1.

- First measurement of these processes at low p_T (>3 GeV)!